Mechanisms of Halo Formation

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Outline

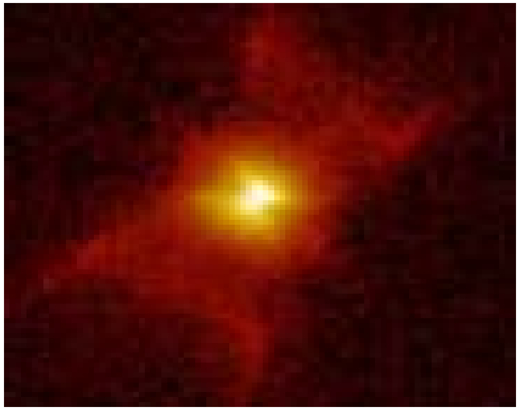
- Beam loss & halo
  - Definition of beam halo
  - List of halo mechanisms
- Basic mechanisms common for linacs and rings
  - Dominant effects
  - Comparison and applications
- Ring specific mechanisms
- Project specific mechanisms

Definition of beam halo

Beam losses associated with a small fraction of particles surrounding a dense beam core – beam halo.

There were many attempts to come up with the definition of beam halo.

Some definitions attempt to distinguish between "halo" and "tails'. Other – assume that the halo is formed due to a specific mechanism and thus the definition includes the knowledge about the structure of the halo.



The usefulness of such "definitions" is not clear.

For beam loss – there is no difference between "tails" or "halo".

There are many mechanisms which lead to halo – trying to make a definition based only on one of them may cause difficulties in understanding of a realistic complex behavior.

Definition (continued)

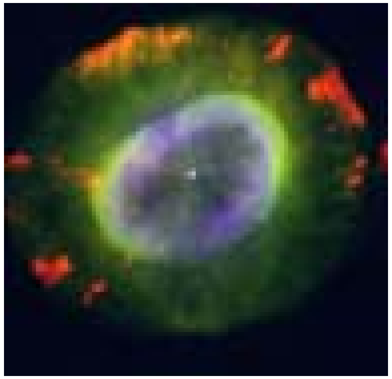
Realizing that "a precise definition" of halo may lead to confusions rather than being helpful we had the following conclusions:

(ICFA Workshop on "Halo and Scraping", Wisconsin 1999):

1. Definition of beam halo is not important.
2. What important are the mechanisms of halo formation – this allows its understanding and possible prevention, as well as provides guidelines for halo observation.
3. It seems sufficient to consider "halo" as it appears to experimentalists - direct link to its observations.

Halo

- Halo – a collection of particles of any origin and behavior which lies in the low density region of the beam distribution far away from the core.



- “Far” stands for “nσ” where “n” maybe = 3, 4, etc:
- depends on the distribution and halo mechanism
- density is rather low at that specific “n”
- because density is so low it is difficult to measure halo
- that is why “halo” is so mysterious – just not easy to observe.
- in most cases it represents a part of the distribution with density below the 1% level.
- stretching the word “halo” to more than a few percent level is not good (it is already beam redistribution). Also, it is then straightforward to measure it.

Partial list of halo mechanisms

High-current linear accelerators:

1. Bad design - anything from RFQ to various sources of machine nonlinearities and misalignments with unavoidable filamentation and halo growth.
2. Rms mismatch
3. Space-charge coupling resonances
4. Space-charge induced structure resonances (90^0 phase advance, etc.)
5. Single and multi-particle scattering
6. Gas scattering
7. Collective instabilities

List of halo mechanisms (continued)

High-current circular accelerators:

8. Additional design contributions – injection, extraction, rf noise, etc.
9. Machine nonlinearities
10. Rms mismatch
11. Space-charge coupling resonances
12. Space-charge induced structure resonances
13. Imperfection lattice resonances
14. Gas scattering
15. Collective instabilities
16. E-cloud effects
17. Project-specific effects – like “banana-shape” driven halo in the SNS Ring

List (continued)

Including short bunches:

18. Transverse-longitudinal coupling
19. Effects from synchrotron motion

Including high-energy accelerators:

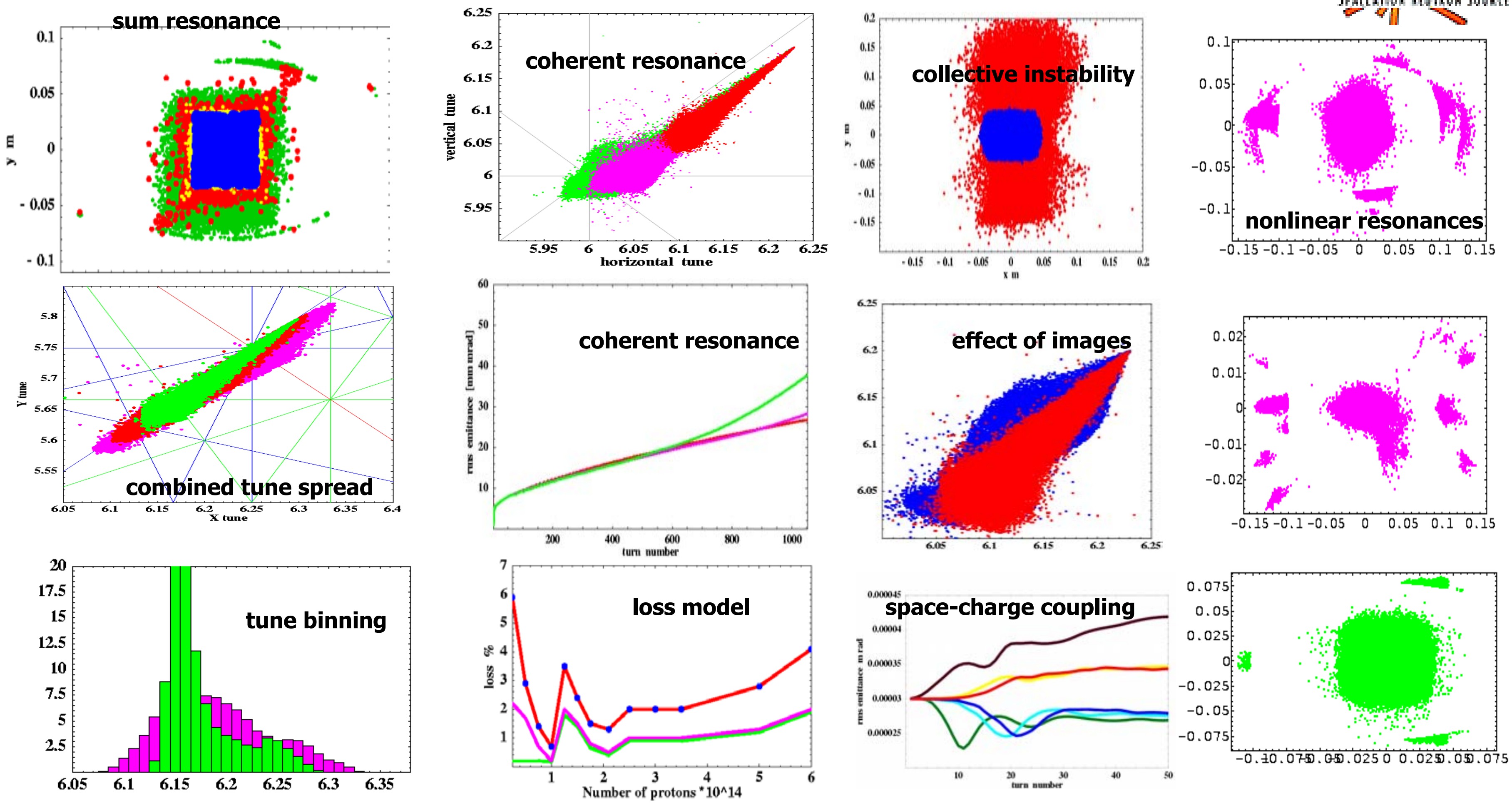
20. IBS
21. Instabilities relevant for high-energy

Including colliding beams:

22. Beam-beam driven halo
23. etc., etc., etc.

and, YES – both longitudinal and transverse halo !

Halo due to various mechanisms in the SNS Ring



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Design & Dynamics contributions
design part

- **Design is critical** - one can prevent some halo formation at the design stage: injection, painting, rf capture & noise, good vacuum, extractions, etc

  Major sources of halo may still exist by design - *Ex*: extraction kickers of the SNS – close orbit does not go through the center of magnets – generates intensity dependent oscillation with a strong emittance increase.

Can we do better?

- Next level in the design topics is to take into account space-charge effects - *Ex*: space-charge induced structure resonances in linacs

  1. Phase advance below 90^0 to avoid second-order structure stopband
  2. etc.

- Control of the "design halo" is possible to some extent, while the dynamics contribution is typically unavoidable which requires halo observation and removal.

Observation of beam halo

Standard way to observe halo:

Stretch out your arm and spread your fingers wide. Cover the bright core with the thumb and the halo will be near the tip of the small finger.

Well, we have to do better than this …

wire scanners, scrapers, hole-drilled screens, filters, etc.

Dominant mechanisms

We summarize only dominant "dynamics" mechanisms, assuming that design topics are under control.

Discussion is limited to general effects which typically are project independent.

Some basic effects common to both linacs and rings are reviewed and differences in their application to linear and circular accelerators are shown.

Examples of some "specific" mechanisms are given.

Space-charge resonances
intrinsic incoherent resonances

- The oscillating space-charge force can lead to a class of resonances where the individual particles inside the beam interact with an oscillating beam modes.

- Such resonances are referred to as "intrinsic" or "incoherent" parametric resonances (Wangler, Gluckstern, et al. - 50+ people 1990-1999, and many papers before '90s, where "emittance growth" was used instead of "halo"):

ν – depressed tune
μ – mismatch parameter
κ - space-charge perveance
a – beam radius
Ω – frequency of beam oscillations

$$x'' + \nu_0^2 x = F_{sc}$$

$$x'' + \nu^2 x = \mu \frac{\kappa}{a^2} x \cos \Omega s$$

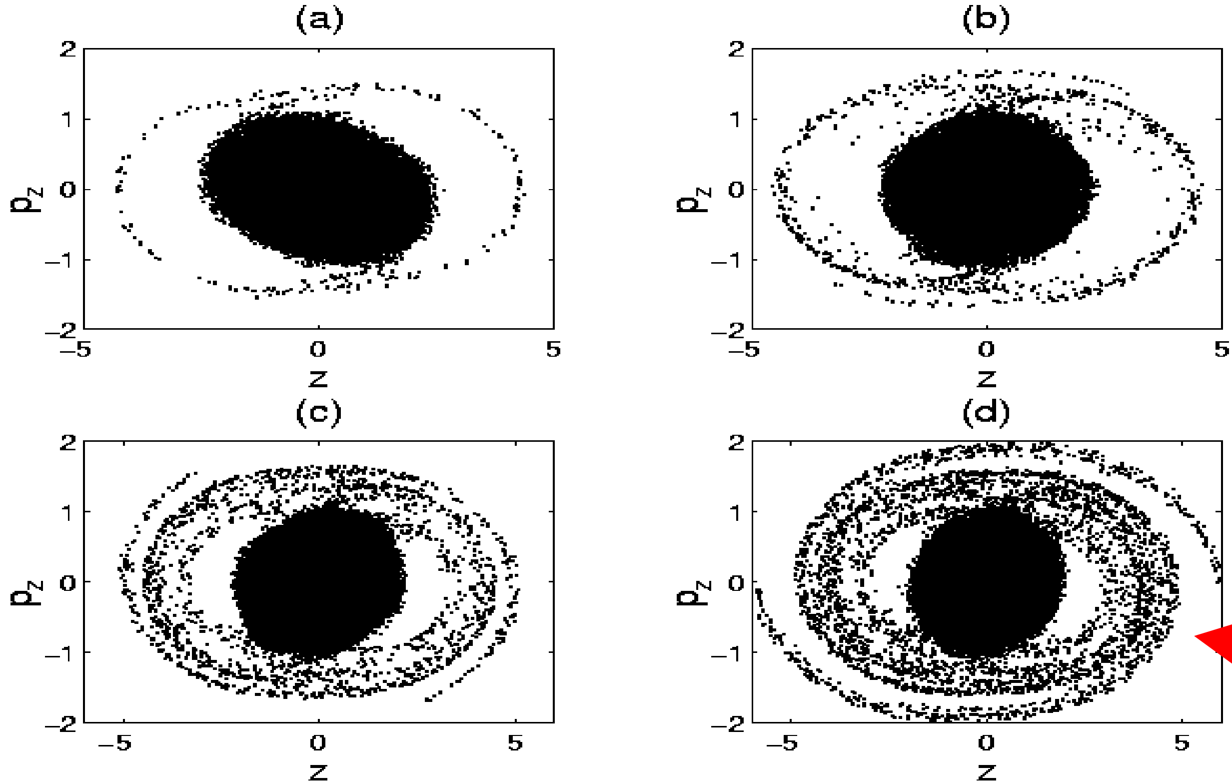
mechanism: parametric resonance

primary resonance (1:2) - $\Omega = 2\nu$

"parametric halo "

Intrinsic incoherent resonances

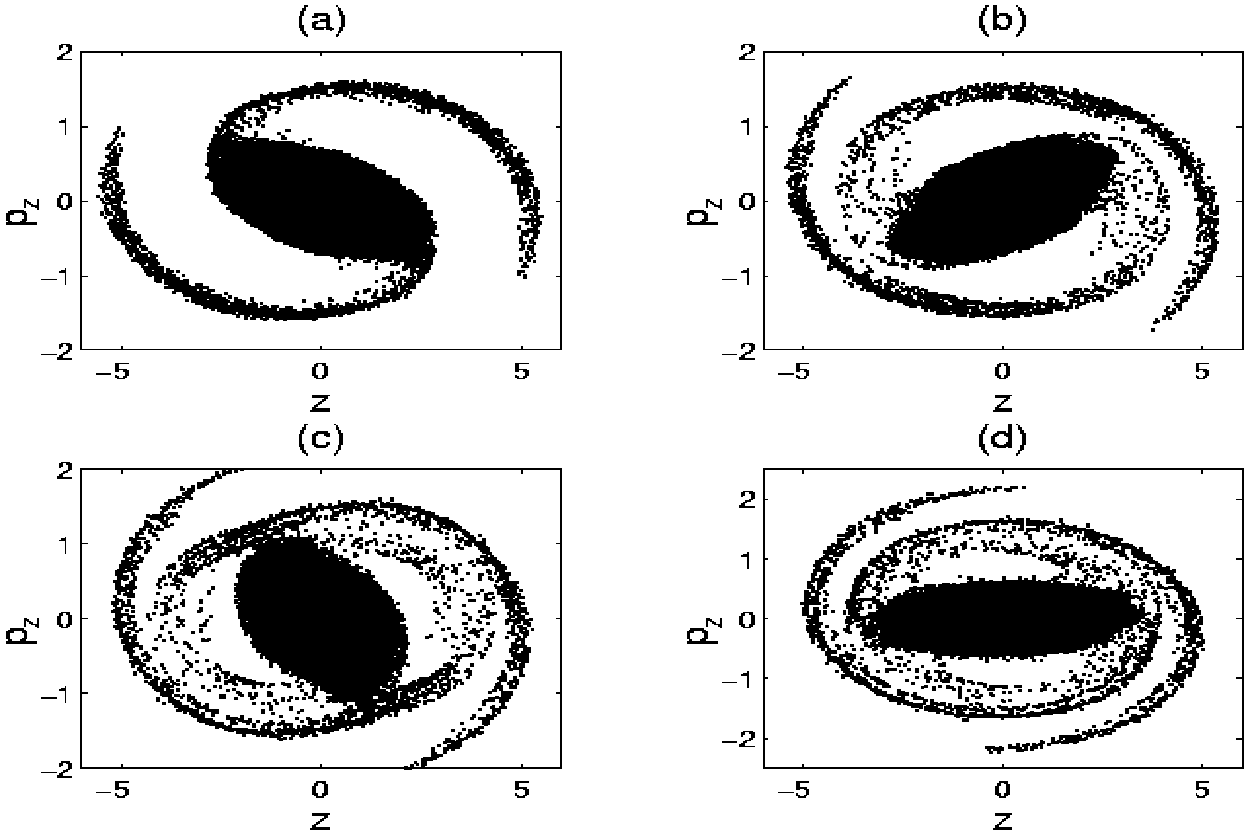
low tune depression – mismatch dependence



Very large mismatch Strong redisrtibution

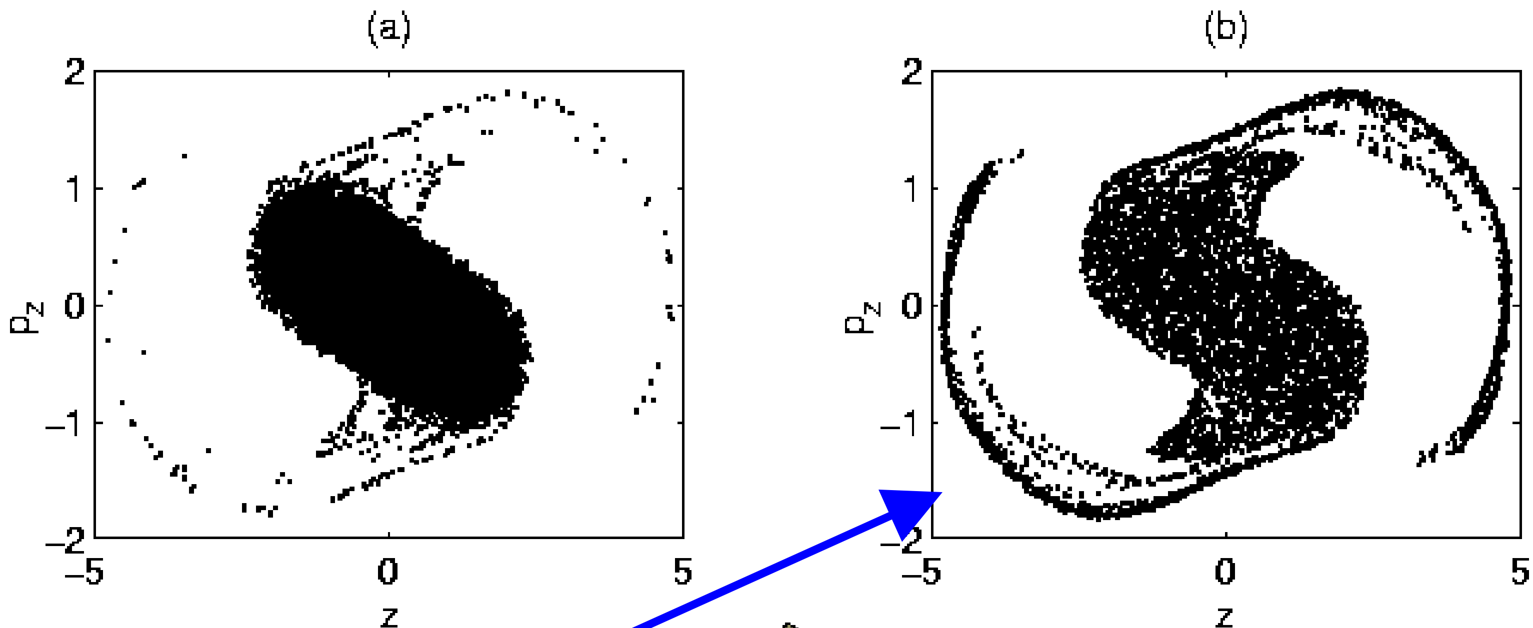
(η=0.93) mismatch parameter μ=1.2, μ=1.3, μ=1.4, μ=1.6

Time evolution of parametric halo with violent mismatch - filamentation



(μ=1.6, η=0.9) at various time periods t=250, t=350, t=450, t=550

Intrinsic incoherent resonances
halo structure

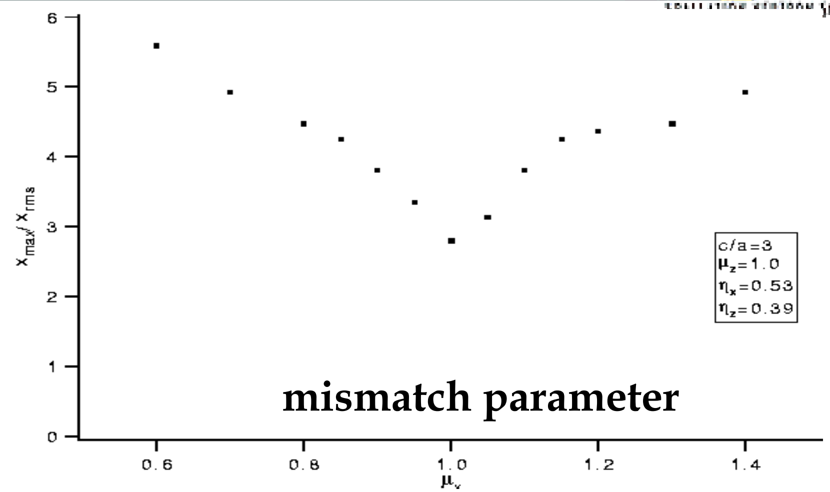


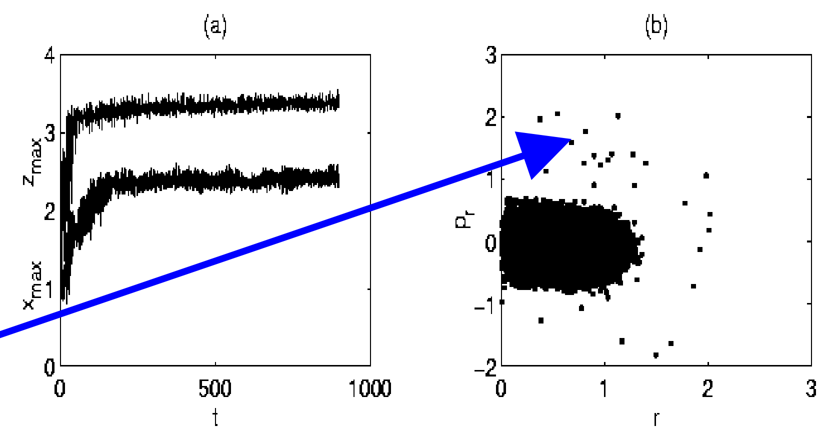
Looking into the halo

allows to study onset of various order resonances and halo structure (Fedotov et al., 1998)

Longitudinal parametric halo and coupling

- Longitudinal halo can have the same mechanism – was studied extensively in linacs ('96-'99).
- For short bunches – halo due to mismatch in one plane can lead to extensive halo in the other due to the coupling ('97-'98).
- Stabilization of longitudinal parametric halo with nonlinear RF in linacs (Barnard, Lund '98)
- Nonlinear rf and longitudinal halo in rings (Fedotov, Gluckstern '99).





coupling effect – development of transverse halo as a result of longitudinal mismatch

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Intrinsic incoherent resonances
rate of halo formation

Rate of halo formation - function of tune depression & mismatch parameter

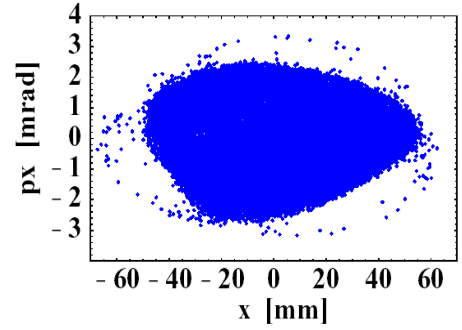
For reasonable mismatches and typical for rings tune depression – it takes much more time for particles to be trapped into the 1:2 resonance than in linacs with strong tune depression.

More importantly, when applied to the accumulator rings – need to take into account many other effects which may destroy the resonance condition: changing beam density and intensity during accumulation, phase-mixing during multi-turn injection, etc.

Taking all these effects into account, simulations for the SNS ring showed that this intrinsic resonance may not be a problem (Fedotov et al., 2000)

However, in rings, collective beam modes can have fast excitation due to the space charge or machine resonances –

"driven incoherent resonances"



Intrinsic halo – comparison

- Linacs – tune depression is very high – rate of such space-charge driven halo can be very fast - warrants consideration.

  Also, one path scenario may allow existence of such resonance

- Rings – tune depression is very weak (unless we are talking "cooler rings" or specific small scale rings for space-charge studies). In addition, there are such effects as multi-turn injection which lead to phase-mixing of oscillating particles, redistribution due to the painting, etc. - may exist, but in many situations it will have a little chance to develop – negligible.

  However, new kind of intrinsic halo does exist (especially in rings) – "driven halo" when collective modes are driven not by a mismatch but rather by the space-charge or imperfection resonances - but such halo we consider anyway when we take into account the effect of resonances in rings.

Space-charge coupling resonances

Space-charge resonances – driven by the space-charge potential itself

Their importance was first shown by Montague (1968) for the coupling resonance:

$2\nu_x - 2\nu_y = 0$ **- does not require perturbation harmonics**

Due to the fact that this resonance is symmetric difference resonance, such a coupling can lead to significant halo only for the beam with unequal emittances.

Analysis of this type of resonances was recently done using a more self-consistent approach of collective beam dynamics (Hofmann, 1998):

$m\nu_x - l\nu_y = 0$ **(single-particle)** $m\nu_x - l\nu_y + \Delta\omega = 0$ **(collective correction)**

Such asymmetric resonances with zero-th harmonic are mainly relevant for linacs where the ratio of the transverse focusing constants can be very different.

Typically, in rings transverse tunes are not very different thus leaving the symmetric Montague resonances as the major resonance with the zero-th harmonic.

Other resonances – when the nonlinear space-charge modes get in resonance with the lattice harmonics (with the space-charge modes being generated by a strong nonlinear space-charge potential in the presence of time-dependent perturbation).

Space-charge coupling resonances - comparison

- **Linacs -** any nonlinear resonances due to a possibility of significantly different focusing constants - results in "equipartitioning charts" which suggest to avoid operation near such resonances – important for consideration since the rate of these effects is governed by the space charge.

- **Rings** – typically not a big split in tunes – mainly symmetric resonance with the zero-th harmonic – as a result – need to worry only for unequal emittances. Also, space charge tune depression is very low – need to consider in many cases.

  Additional effects due to imperfection harmonics (Machida et al. 1991-): need to consider the nonlinear space-charge coupling resonances with the lattice harmonics

Space-charge structure resonances

When collective modes of beam oscillation resonate with the lattice structure (Hofmann et al, 1983, Okamoto et al. 2001):

$$N/2=\Omega_m$$

where N is the structure harmonic and Ω_m is the frequency of oscillation of m-th order collective beam mode.

↓

For m=2 (envelope modes) $N/2=\Omega_2$ - this is known as the "envelope instability" (Struckmeier, Reiser, 1984)

↓

Large halo growth

Space-charge structure resonances - comparison

- Linacs - important since tunes are not limited by imperfection resonances and thus tune depression can be increased until one hits structure stopbands

  -90^0 phase advance

  -60^0 (if 3^{rd} order modes are driven)

- Rings – same problem if emittance growth due to the imperfection resonances can be minimized like in cooler rings with additional external cooling force.
- Otherwise – intensity is already limited due to the halo driven by the imperfection resonances.

Single and multiple scattering

- **Linacs – one can get a halo shell surrounding the beam which would look similar to the one due to a mismatch halo – "what do you expect? – it is halo after all".**
- **However, calculated scattering rates (with space charge) showed that the process is too slow to be important for linacs (Gluckstern, Fedotov, 1999, Pichoff, 98-99)**

Simple analytic expressions in terms of beam parameters were obtained

$$f(\boldsymbol{r},\boldsymbol{v}) = \begin{cases} N(H_0 - H)^n = N[G(r) - mv^2/2]^n, & H < H_0, \\ 0, & H > H_0, \end{cases} \qquad G(r) \equiv H_0 - kr^2/2 - e\Phi_{\mathrm{sc}}(r).$$

$$\frac{dP}{cdt} \sim \begin{cases} r_p^2/\epsilon_N^3, & n > 0, \\ (r_p^2/\epsilon_N^3)\ln(\epsilon_N^2/r_p a), & n = 0, \\ (r_p^2/\epsilon_N^3)(\epsilon_N^2/r_p a)^{-n}, & 0 < -n < 1 \end{cases}$$

Coulomb scattering – rate in linacs

Probability of ions to leave the bunch per unit length

$$\frac{dP}{c\,dt} \sim \begin{cases} 10^{-15}/\mathrm{km}, & n > 0\,, \\ 10^{-14}/\mathrm{km}, & n = 0\,, \\ 10^{-11}/\mathrm{km}, & n = -0.5\,, \\ 10^{-8}/\mathrm{km}, & n = -0.9\,, \end{cases}$$

For typical beam parameters in a linac:

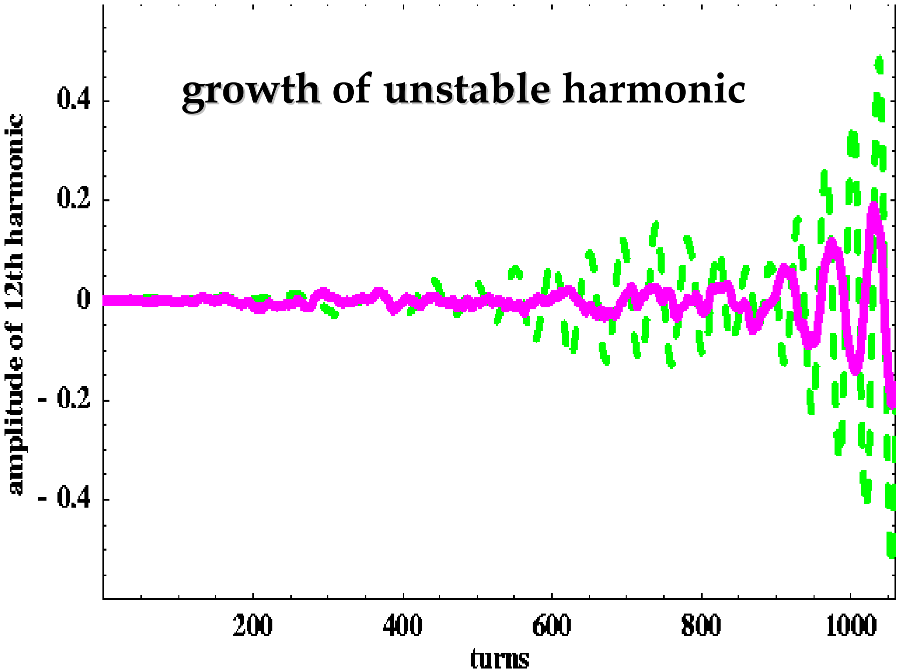
- Relatively singular distribution → 10^{-8}-10^{-11}/km
- Waterbag distribution → 10^{-14}/km
- Gaussian-like distributions → 10^{-15}/km

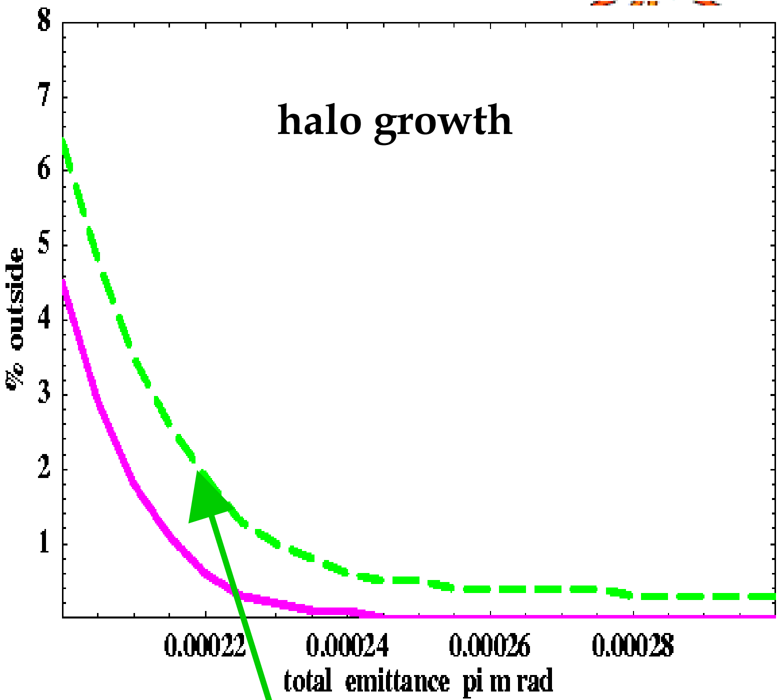
Linacs - diffusion is too slow to be important.

Caution: simulations can give "numerical" halo.

Rings: - for long storage times IBS is the dominant effect

Halo due to collective instabilities:
SNS extraction kicker impedance, N=1.5 *10^{14}





Green – zero chromaticity – unstable - halo

Pink - chromaticity (-7) – "stable" –

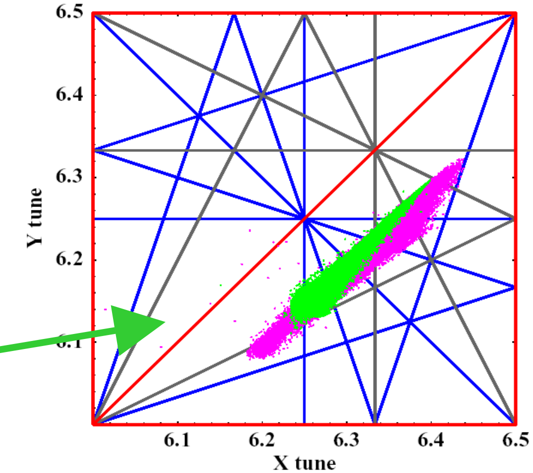
small growth rate but no halo

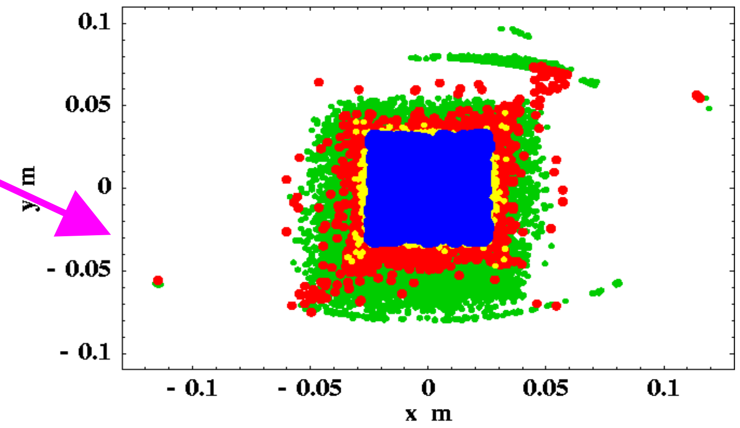
Ring specific effects:
imperfection lattice resonances

In this example, resonances are crossed due to the space-charge tune depression.

Space charge plays an important role:

- It creates a problem since the tunes are depressed by the space charge towards the resonances
- It introduces an effective nonlinearity which changes beam response
- Collective beam response $n=\Omega_m$





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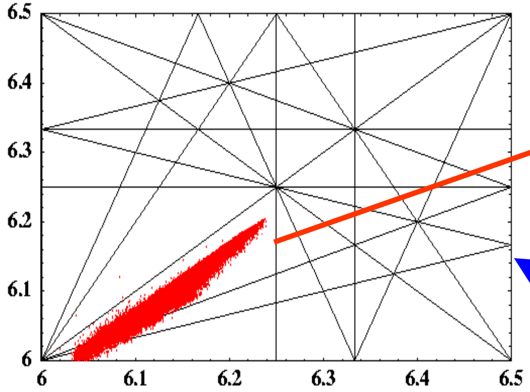
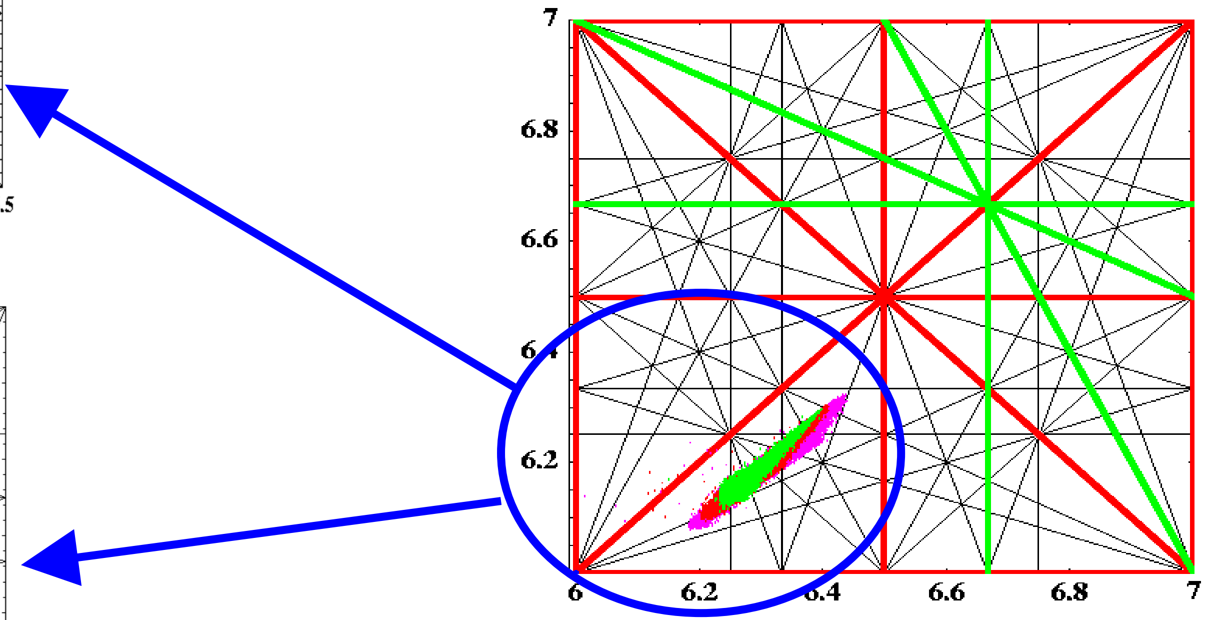
Lattice resonances

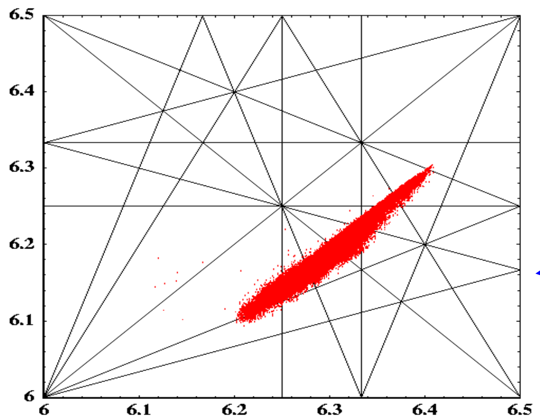
selection of working points to avoid emittance growth in high-intensity rings



Space-charge spread of
2 MW SNS beam



w.p. below ¼ tunes



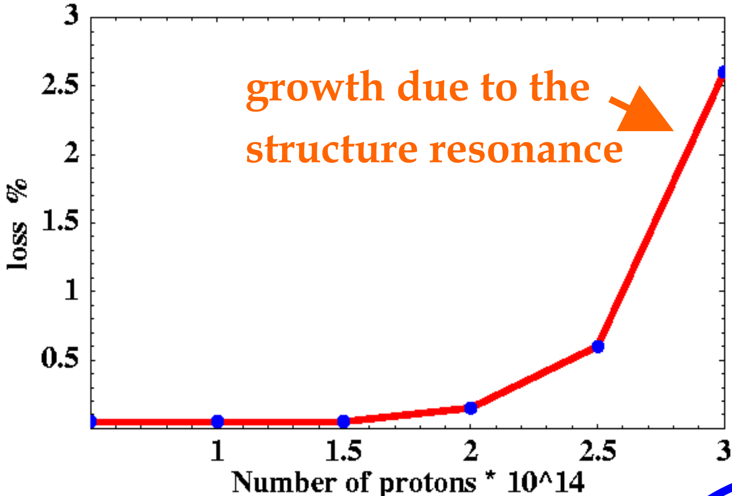
w.p. above ¼ tunes

Lattice resonances
beam halo due to nonlinear resonances

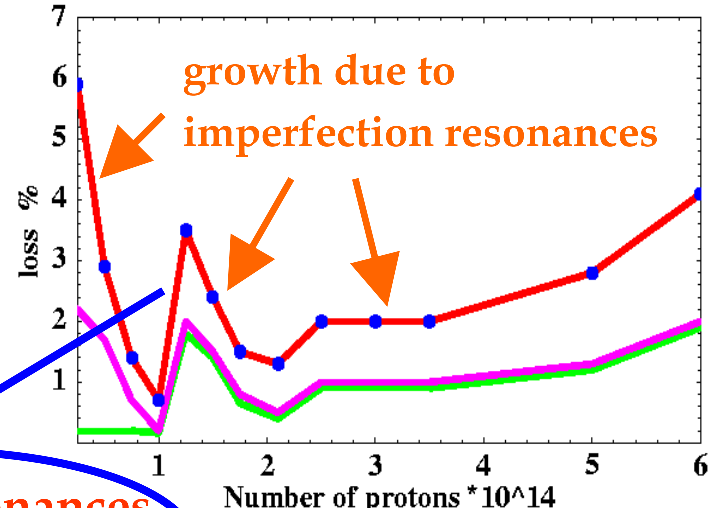
SNS examples

realistic simulations with the UAL code

w.p. below ¼ tunes



w.p. above the nonlinear resonances of 4th and 3rd order



requires resonances correction

Lattice resonances
correction of nonlinear resonances & space charge

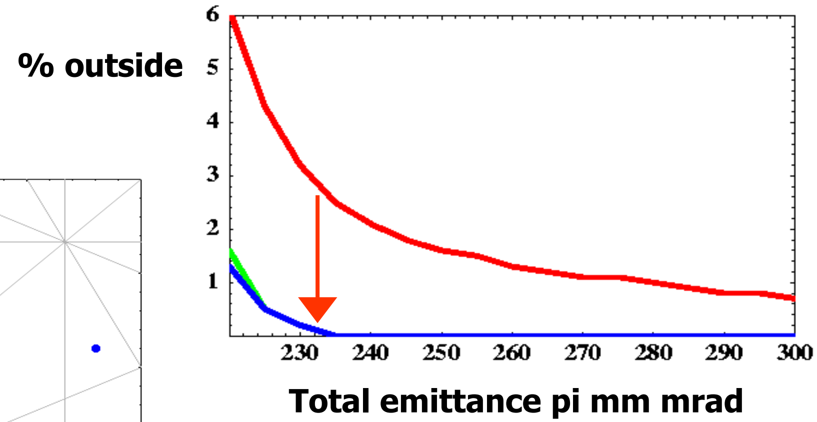
Example: SNS w.p. (6.36, 6.22) - correction of 3Qx=19 and 2Qy-Qx=6

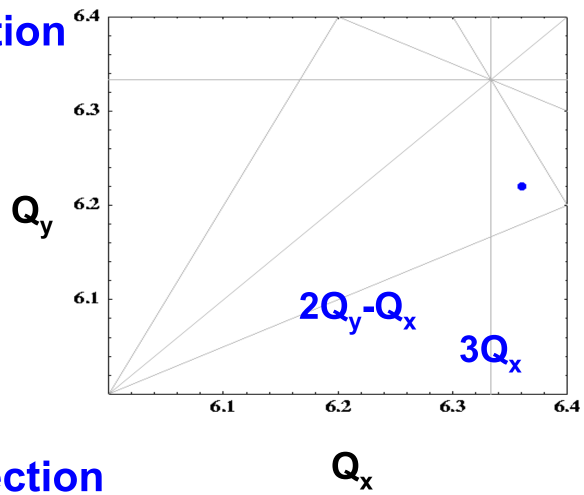
N=0.6*10^14

blue – no errors

red – errors, no correction

green – errors, correction of 3Qx=19 resonance





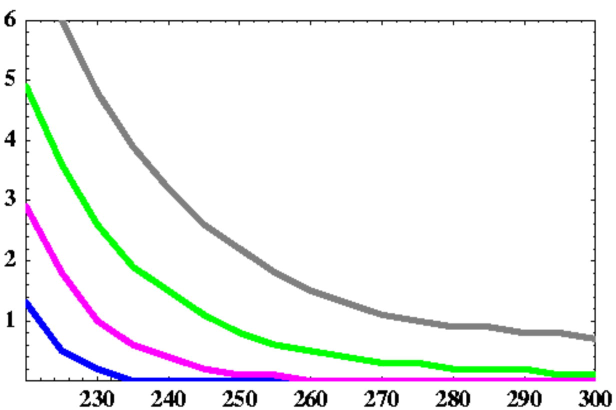
N=2*10^14

blue – no errors

grey – errors, no correction

green – errors, correction of 3Qx=19

pink – errors, simultaneous correction of 3Qx=19 and 2Qy-Qx=6 resonances

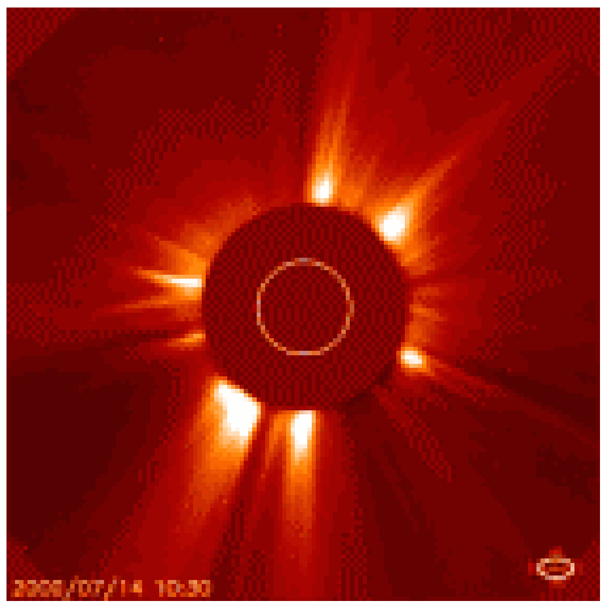


Some examples of “project-specific” halo

EXAMPLES OF

SNS RING SPECIFIC

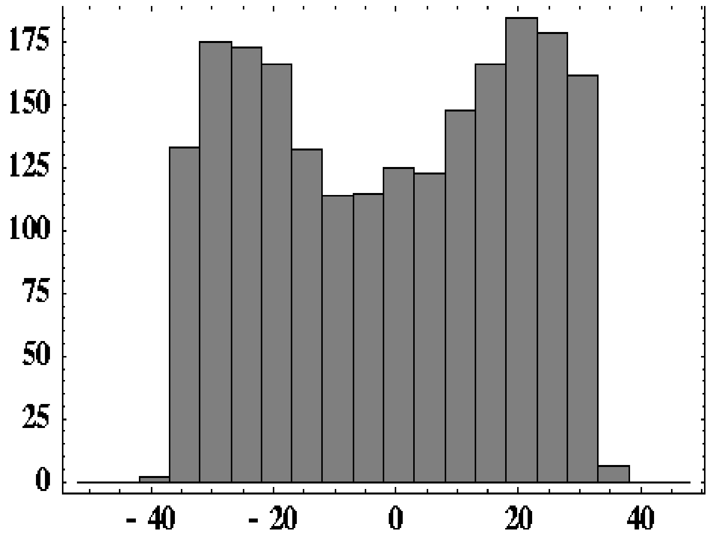
HALO MECHANISMS



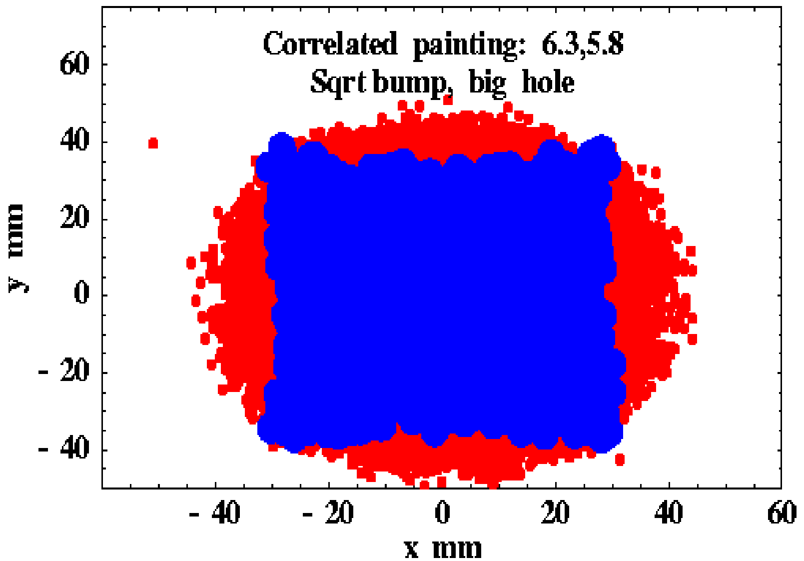
Space-charge induced halo in painting

Significant "hole" (closed orbit offset) in painted distribution is necessary to satisfy Target requirement (more uniform density) –
as a result, square-shape beam profile is not preserved with the space charge (SC).

1-D density plot in Y without SC.



Beam profile with and without SC

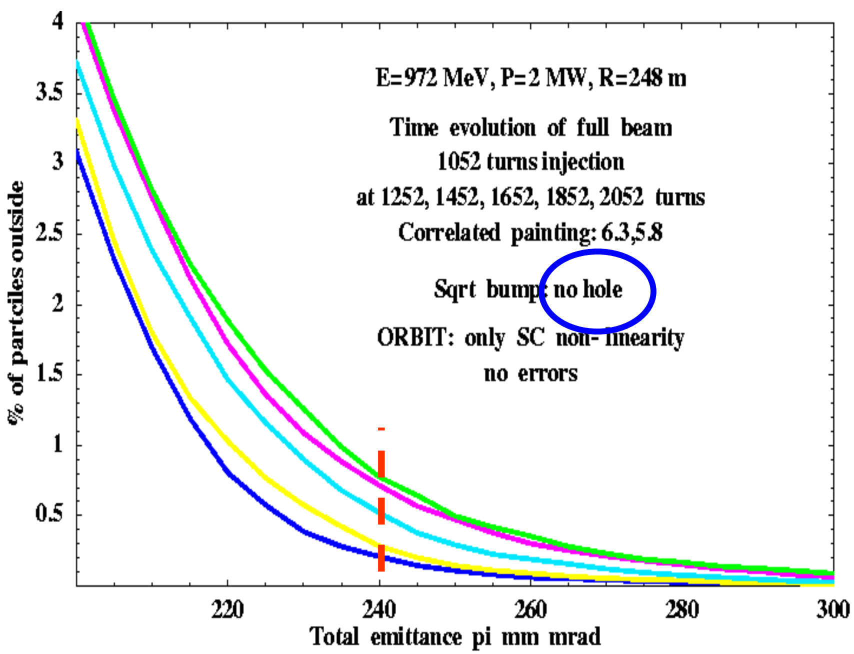


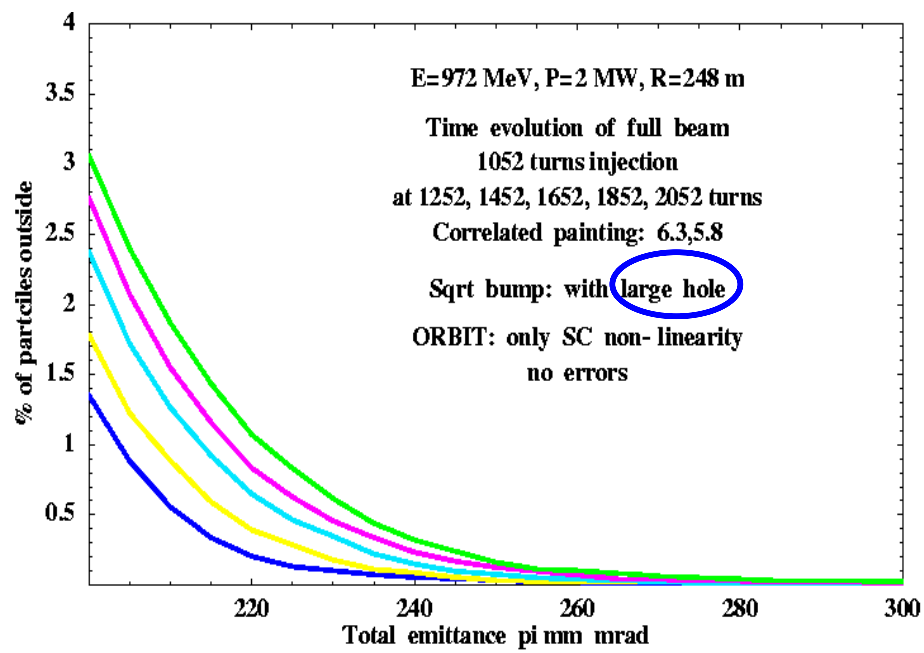
Time evolution and diffusion of distributions

Spreading of beam distribution based on painting without a hole (no c.o. offset). Multi-turn injection stops at 1052 turns.

Spreading of distribution based on painting with significant hole (c.o. offset). Multi-turn painting stops at 1052 turns.

Spreading is shown at various time steps from 1252 turns (Blue) to 2052 turns (Green)

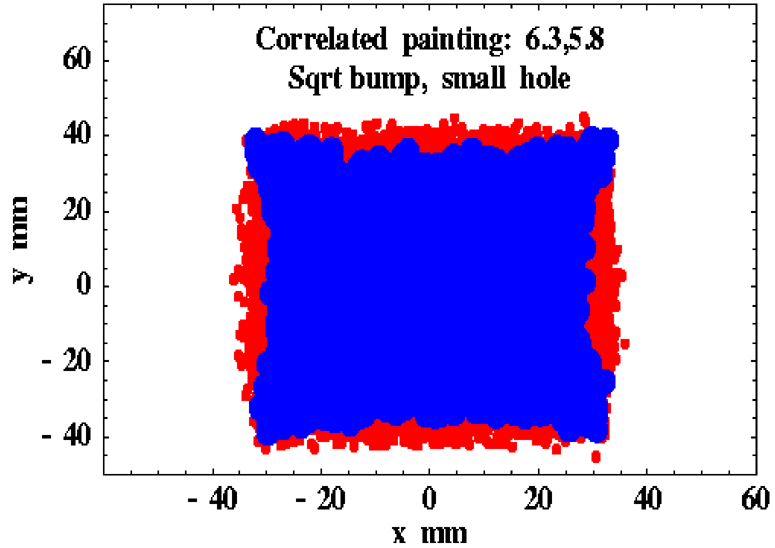




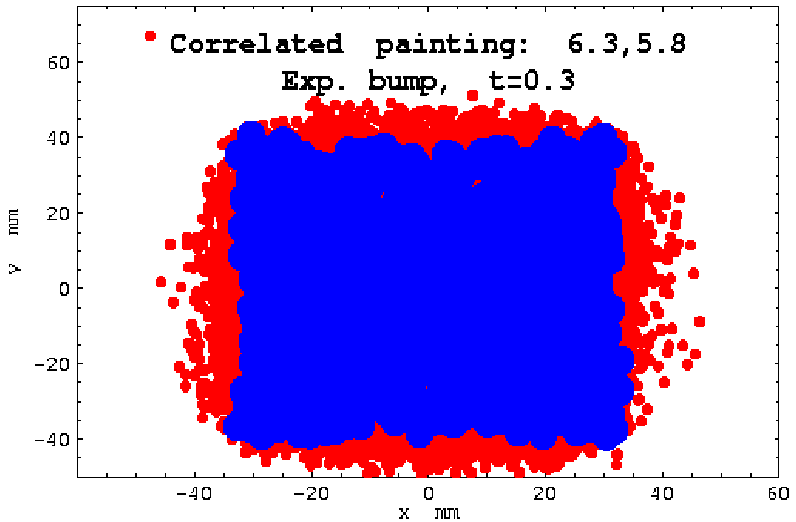
Different injection bump functions

Beam spreading and associated halo strongly depends on bump function. Examples are given for sqrt and exponential functions with and without SC.

Sqrt()

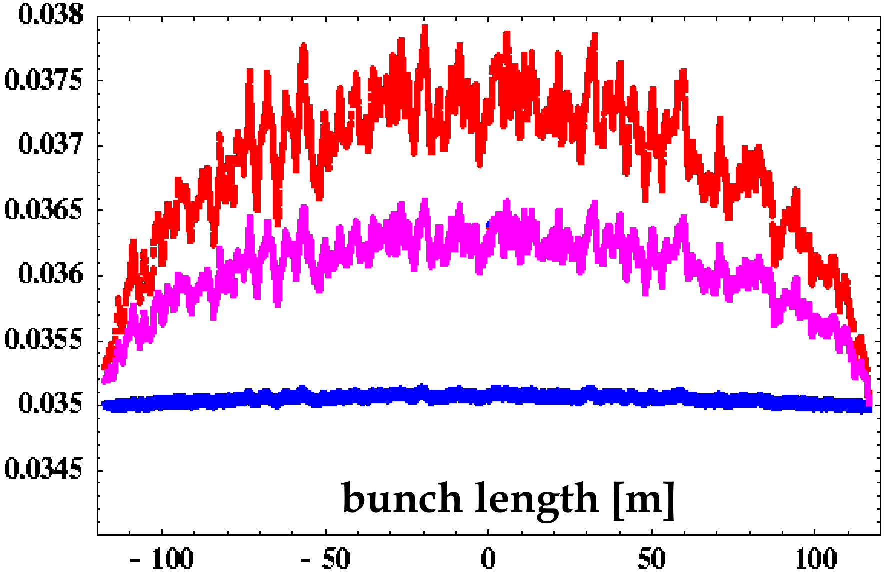


Exp()

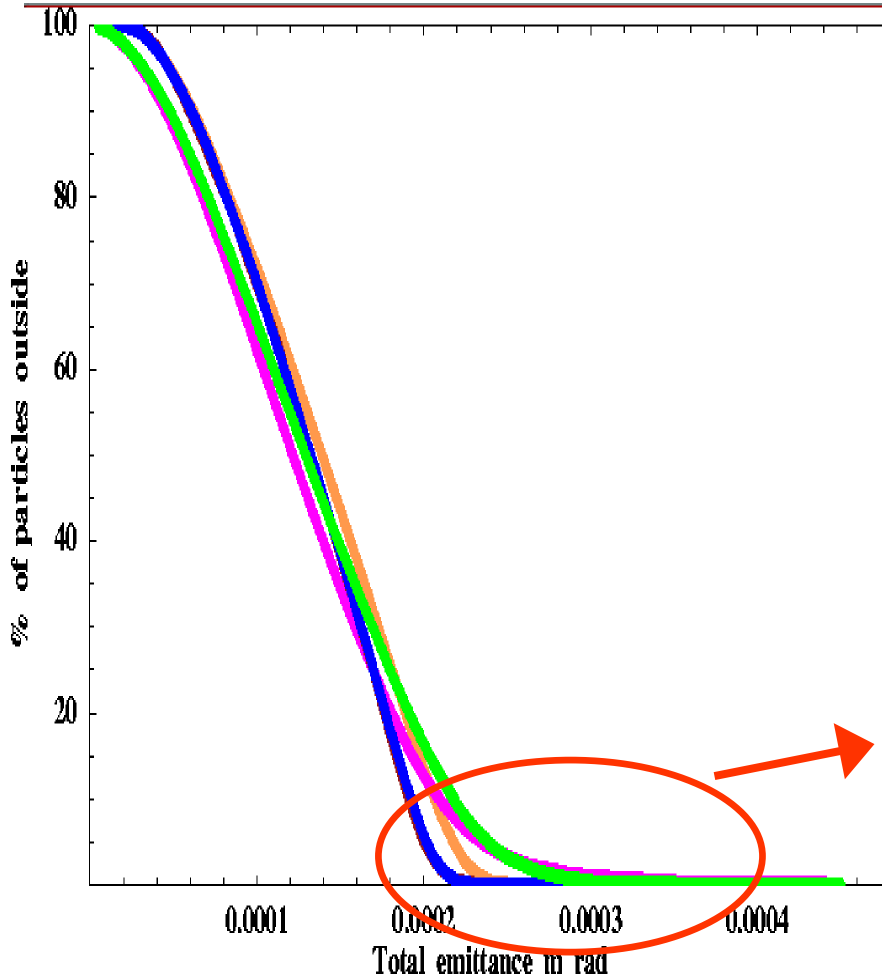


Extraction Kicker offset

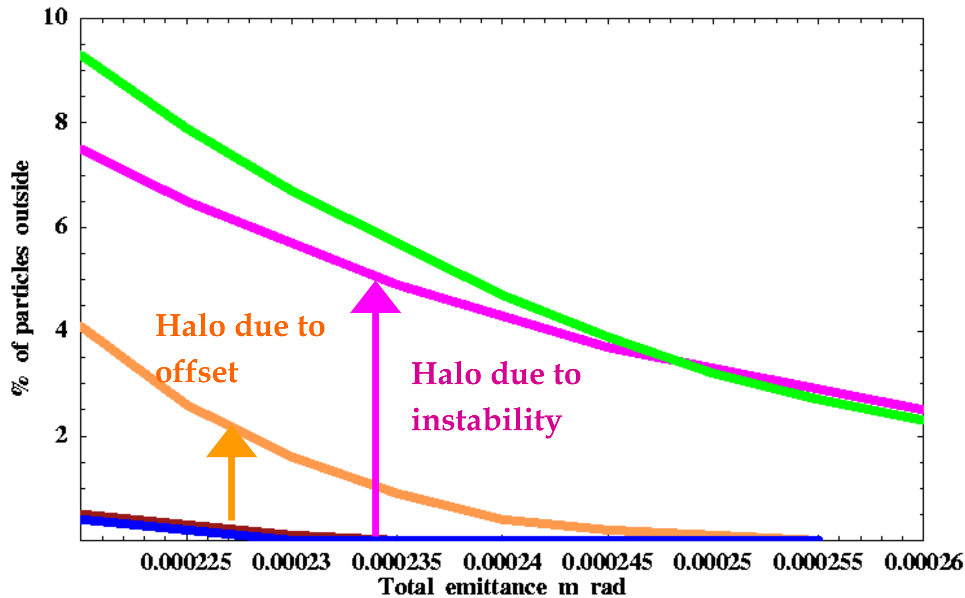
- Extraction Kickers are offset from the center to save on mechanical dimensions when the full-size accumulated beam is extracted.
- Due to longitudinal current distribution along the bunch center of the beam will experience a kick different from the head and tail which results in a "banana-shape" distortion.
- Emittance growth associated with this effect was explored.
- Largest offset is in second 7-kicker module (from 2.9 cm to 4.3 cm).



Effect of kicker offset on halo
(after 1060 turn accumulation, N=2*10^{14})



Blue- no SC, impedance, no offset
Brown –no SC, no impedance, no offset
Orange – no SC, impedance with offset
Pink – SC, impedance, no offset
Green – SC, impedance with offset



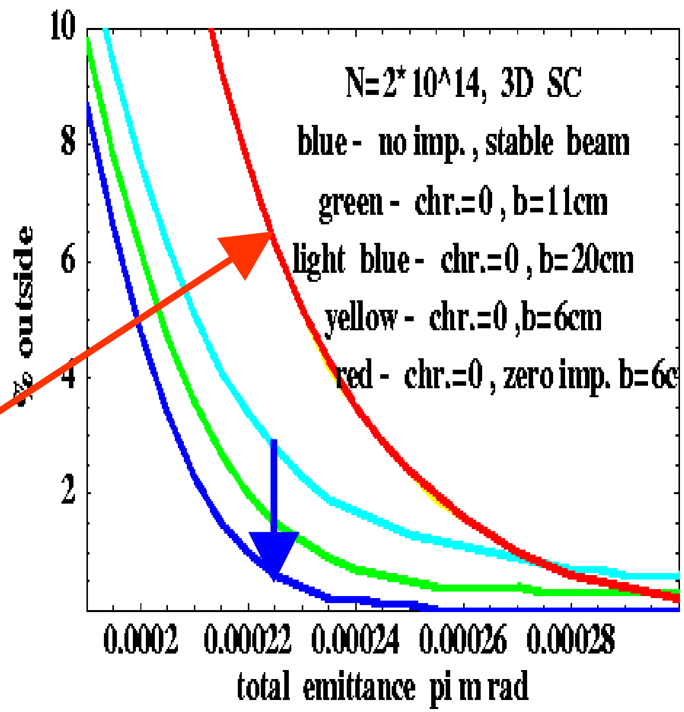
b/a dependence ("effect of images") – halo due to collective instabilities (b/a- pipe/beam radii)

1. b/a variation along the bunch introduces effective tune variation (due to longitudinal current density) and thus plays stabilizing role.

- Making ratio b/a larger decreases stabilization and makes beam more unstable with larger halo

2 . If b/a is too small one gets into the region where image effects play the dominant role. Even though unstable harmonics due to impedance are stabilized, there is now a significant halo growth associated with this effect.

It is not related to Extraction Kicker impedance instability, as shown in the Figure, where emittance growth with and without impedance for small b/a is the same (shown with yellow and red colors, respectively).



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Comments on numerical halo

- Although analytic models and basic physical pictures are required to understand halo formation, the final conclusions are typically drawn from realistic simulation.

If simulation involves interaction between particles:

1. Find saturation of diffusion in your numerical system first – numerical halo is nice – “not thrilling, but nice”.
2. Even when saturation of numerical parameters is found on some fixed time scale – there is still diffusion on a longer scale:

   If there is some diffusion in your simulation which looks “fishy” – it is probably an art effect of your simulation.

General comments

- It is important to keep in mind that there are many mechanisms of halo formation.

- Obviously, when several mechanisms are present simultaneously, one gets a complex behavior - typically requires realistic simulation.
- Physics of some mechanisms can be the same in linacs and rings – but application of these mechanisms may be very different.
- There can be always some “machine-specific” dominant mechanisms so that general mechanisms should not be taken for granted – trust but double check.

Future of beam halo

Future of beam halo – looks good.

Despite our understanding of some mechanisms of halo formation, design choices to avoid halo and halo removal – halo and emittance growth due to something else will be always there.

There will be plenty of work for graduate students and enough subjects to discuss at the Workshops:

Have a Good Time at the Workshop!

Acknowledgments

I would like to thank many collaborators with whom I worked on the subject of beam halo in linear and circular accelerators, as well as the SNS Accelerator Physics group for numerous useful discussions on this subject:

R.L. Gluckstern, T. Wangler, R. Ryne, S. Kurennoy, N. Pichoff, I. Hofmann, J. Holmes, S. Cousineau, S. Danilov, Y.Y. Lee, J. Wei, D. Raparia, M. Blaskiewicz, G. Parzen, N. Malitsky and many other